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A prototype portable biomass pyrolysis unit and its potential to produce value-added chemicals and fuel

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Abstract

The world's petroleum reserves won't last forever, and their use for fuel increases greenhouse gas emissions that contribute to climate change. Renewable biomass is a promising alternative to petroleum-based products as a source for bioenergy and other bioproducts (e.g., value-added chemicals, food additives) but comprises only a minor portion of the world market. We describe a prototype portable fast pyrolysis unit made in Ontario as an example of an emerging biomass conversion technology. We also summarize the possible value-added chemical and biofuel uses of bio-oil. Challenges to commercializing this emerging technology are discussed.

Introduction

Although the world's economy still depends on non-renewable fuel and chemicals made from refined petroleum, sustainable bio-based fuels and chemicals are gaining in market share (Carlson 2011). Prices for petroleum feedstocks used for fuel and value-added chemical production are usually lower, but increasing global demand has increased their value, while costs for biomass-based feedstocks are dropping (van Haveren et al. 2007). And biomass is the only sustainable source of carbon-based fuel and value-added chemicals (Sheldon 2011). As with petroleum, biofuel could be made more profitable by co-producing value-added chemicals, but today only 1 to 2% of the overall worldwide chemical production is bio-based (Carlson 2011).

One of the keys to making bio-based fuels and chemicals more affordable is developing better technology. Some companies do have biofuels as an important part of their product line, but it will be years before these products will replace petroleum-based fuels (Hayden 2011). Recent increases in demand for and price spikes in natural and fossil fuel-based rubber compounds have increased commercial efforts to develop bio-based chemicals for use in rubber tires (Bomgardner 2011). A bio-based tire chemical that is almost ready for marketing is bioisoprene, which one developing company, Amyris, expects to start producing at commercially competitive prices by 2015 (Hayden 2011). Developing value-added bio-based chemicals is critical to a commercially viable biofuel industry (Bozell and Peterson 2010).

Value-added bioproducts have been more challenging to produce commercially than the convergent (single product) biofuels industry because of the many possible products and technologies (Bozell and Peterson 2010). Biomass pyrolysis is the most economical technology for producing both bio-based fuels and value-added chemicals from bio-oil (Vispute et al. 2010). Focusing on the most economical technology to produce the most promising value-added bio-products is the best approach to develop commercial bioproducts (Bozell and Peterson 2010). In Canada, a study funded by the Forest Products Association of Canada (FPAC) concluded that several technologies, including stand-alone pyrolysis, hold considerable promise for commercialization of bioproducts (FPAC 2010). Given the interest in sustainable fuel and bioproducts, the

main objective of this note is to describe prototype portable pyrolysis unit formerly owned by the Ontario Ministry of Natural Resources (MNR) and outline the possible uses of its pyrolysis oil. A second objective is to provide a summary of challenges to the commercialization of bio-oil for biofuels and value-added products.

Pyrolysis

Pyrolysis is a robust thermochemical process that transforms organic material into liquid (bio-oil), solid (biochar), and gas (syngas) using extreme heat (usually $\geq 400\text{ }^{\circ}\text{C}$) in the absence of oxygen (Bridgwater et al. 1999, Laird et al. 2009). The main objective of pyrolysis is to convert low density biomass into dense, high energy liquids or solids (Laird et al. 2009). The four types of pyrolysis are:

- *Slow pyrolysis*: The leading method of producing bio-oil (Mohan et al. 2006, Laird et al. 2009), slow pyrolysis involves slowly heating biomass to the desired temperature and produces, on average, about 30% bio-oil, 35% biochar, and 35% syngas (IEA 2007, Laird et al. 2009)
- *Gasification*: A controlled amount of oxygen is combined with the biomass, causing partial combustion and maximizing the production of syngas (Bridgwater et al. 1999). The reaction temperature is higher (usually $>800\text{ }^{\circ}\text{C}$) than that used for other pyrolysis systems, and the process produces about 5% bio-oil, 10% biochar, and 85% gas (IEA 2007).
- *Flash pyrolysis*: Designed to maximize biochar, this system involves placing batches of biomass under moderate to high pressure, usually producing 60% biochar and 40% volatiles (syngas and volatile bio-oil) (Laird et al. 2009).
- *Fast pyrolysis*: With rapid heating of biomass to maximize the yield of bio-oil, this system typically produces 50 to 70% bio-oil, 10 to 30% biochar, and 15 to 20% syngas (Laird et al. 2009). To maximize the efficiency of fast pyrolysis, fine biomass particles are combined with temperatures ranging from 400 to 550 $^{\circ}\text{C}$ (Bridgwater et al. 2007). The entire process generally occurs in less than 2 seconds to maximize bio-oil yields and limit secondary reactions that form gases (Bridgwater et al. 1999, Mohan et al. 2006).

Mohan et al. (2006) describe five types of fast pyrolysis reactors that produce acceptable yields of bio-oil: *ablative*, *auger*, *fluid bed*, *circulating fluid bed*, and *vacuum*. We describe only the fluid bed and auger type, because the fluid bed is the most common and the MNR pyrolysis unit is a hybrid auger/fluid bed type. Fluid beds and circulating fluid beds normally use sand or other solid material such as stainless steel balls heated to between 450 and 800 $^{\circ}\text{C}$ as the heat transfer mechanism. Auger pyrolysis units use augers or screws to mechanically move biomass through the unit rather than moving it with steam or an inert gas such as nitrogen. However, these units often heat biomass with steel or ceramic balls or sand that circulates through the auger, making them a hybrid-type pyrolysis unit with both auger and fluid bed characteristics. The heat is transferred quickly from the auger and/or fluid bed to the biomass by convection and conduction (Farag et al. 2002), and the resulting vapours are rapidly cooled and condensed to form a liquid bio-oil (Laird et al. 2009). The biochar and syngas produced can be recycled to produce the heat needed to drive pyrolysis (Mohan et al. 2006).

Bio-oil properties and characteristics

Bio-oil is a dark brown, acidic, mostly organic liquid with a smoky odour (Mohan et al. 2006). This high-density (1.2 g cm^{-3}), free-flowing liquid has nearly half the heating capacity of residential heating (No. 2 fuel) oil, but due to its high water content does not mix with petroleum products (Czernik and Bridgwater 2004). The energy density of bio-oil is 6 to 7 times greater than that of raw woody biomass and is its main advantage over bulky and expensive to transport biomass when comparing their use as an energy source (Badger and Fransham 2006). Because biomass is high in carbohydrates, its compounds have a high oxygen concentration (Mohan et al. 2006). These oxygenated chemicals are reactive, resulting in gradual changes in the chemical composition and properties of bio-oil during long-term storage (Diebold 2000).

Bio-oil is a complex mixture of more than 300 organic compounds, including aldehydes, carboxylic acids, ketones, phenols, polysaccharides, and alcohols plus water (Tsai et al. 2007, Zhao et al. 2010). Water is the most abundant compound (15-30%) (Zhang et al. 2007), usually followed by glycolaldehyde, acetic acid, and hydroxyacetone (Table 1). Other abundant compounds include furfural, formic acid, levoglucosan, glyoxal, syringol, guaiacol, eugenol, vanillin, coniferaldehyde, and phenols (Hosoya et al. 2007, Vitasari et al. 2011). The final chemical composition depends on the reaction conditions and the type of biomass feedstock (Mohan et al. 2006).

Table 1. Main biochemical components of bio-oil derived from various types of woody biomass.

Chemical	Forest residue (Vitasari et al. 2011)	Pine/spruce wood (Dynamotive 2011a)	Wood (Diebold 2000)
	Wet weight (%)		
Glycolaldehyde	6.2	9.4	0.9–13
Acetic acid	6.2	4.5	0.5–12
Hydroxyacetone	4.0	6.6	0.7–7.4
Glyoxal	n/a*	2.3	1.05
Furfural	0.7	n/a	1–1.1
Levogluconan	1.7	7.3	4.8–5.4
Formic acid	n/a	4.6	0.3–9.1
Cellobiosan	n/a	2.3	0.6–3.2
Syringol	0.3	n/a	1.4–8.8
Guaiacol	0.2	n/a	2.2–15.1

*n/a = not available.

Prototype portable pyrolysis biorefinery

To help promote bioenergy development and demonstrate the concept of a portable biorefinery, MNR commissioned a 50-ton-per-day portable fast pyrolysis unit (Badger and Fransham 2006). The biorefinery was built by Advanced Biorefineries Inc. and assembled by Penguin Automated Systems Inc. (Penguin ASI) who also designed and made the control systems. It requires 6 flatbed transport trucks or 4 rail cars to move it from one location to another (Figure 1) and about 1 week to assemble all components. The MNR biorefinery has 7 main components (Figure 2) that perform the following functions:

1. Raw wood chips are dumped onto the *inclined hopper* that transfers them onto
2. a *conveyor belt* that drops the biomass into the
3. *dryer and pulverizer*. Here a hot air stream dries the biomass to $\leq 10\%$ moisture content while chips are pulverized into tiny particles, less than 2 mm in diameter, by rotating chains. A blower then moves the small particles up a duct and deposits them into two
4. *conical cyclone separators* that also temporarily store the biomass. The whirling cyclone separates the hot air and steam from the biomass by spinning it around the edges of the cone. Friction with the cone walls causes the biomass to drop to the bottom of cone where it collects until it is passed through an air lock and is fed into an airless auger that transfers the biomass into the
5. *pyrolysis reactor*. Another auger then moves the biomass and steel shot, heated to about 500°C by the
6. *heater*, into a reaction tube where pyrolysis occurs within a second or two. The resulting gas and hot vapours are then sent to the two
7. *condensing tanks* where hot vapours are rapidly cooled and condensed into bio-oil while the non-condensable synthesis gas is siphoned off and recycled to the heater for use as fuel. These condensers also serve as temporary storage tanks for the bio-oil. Meanwhile steel shot and the solid bits of biochar are removed from the reactor tube and augered into the heater where the charcoal is burned to heat up the steel shot that is continuously recycled back into the reactor.

The MNR biorefinery is an auger type pyrolysis unit that is augmented by heated steel shot circulating through the pyrolysis reactor. This really makes it a hybrid auger-fluid bed type pyrolysis unit with the steel shot serving as the fluid bed. The advantage of auger pyrolysis units is that they do not require a carrier gas and operate at lower ($400\text{--}500^\circ\text{C}$) process temperatures (Mohan et al. 2006). The disadvantage of auger units is that they have moving parts in the heated zone and heat transfer may be a problem when they are scaled up to large commercial operations (Mohan et al. 2006). However, compared to a pyrolysis unit just using an auger, the steel shot in the MNR pyrolysis unit should improve heat transfer to the biomass in the reactor.



Figure 1. Loading conical cyclone separators that are part of the Ontario Ministry of Natural Resources' pyrolysis unit onto a flatbed truck for transport.

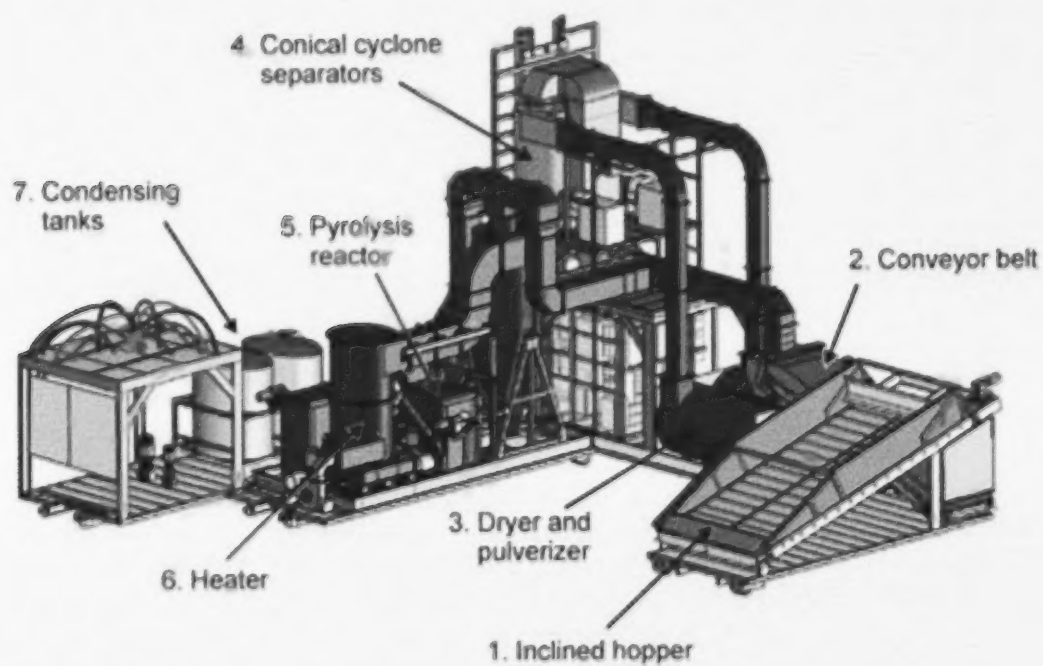


Figure 2. The Ontario Ministry of Natural Resources' pyrolysis unit.

Bio-oil production and storage stability

In November 2009, the MNR biorefinery was operationally tested by Penguin ASI and successfully produced a batch of bio-oil. Red oak sawdust was used as the biomass source (Figure 3). The biomass required about 1 minute from the time it was loaded into the biorefinery until the final bio-oil product was collected in the condensers. The pyrolysis was done in the reactor tube with steel shot heated to about 500 °C. The bio-oil produced was reddish brown in colour and had a thin layer of black biochar that precipitated out and settled to the bottom of the container (Figure 4).



Figure 3. Using inclined hopper to load oak biomass into the Ontario Ministry of Natural Resources' pyrolysis unit.



Figure 4. Bio-oil generated with the Ontario Ministry of Natural Resources' pyrolysis unit in November 2009.

To test the storage stability of the MNR unit's bio-oil and to generally characterize its chemical components, a 100 ml sample was provided to the Ontario Forest Research Institute for analysis. The bio-oil was stored in the dark at 4 °C until analysis; no visible phase separation occurred during storage. Two 2 ml samples of filtered (Whatman #1 filter paper) bio-oil were placed in a Petri dish and dried in an oven at 40 °C for 21 hours (July 2010) and 4 days (July 2011) until most water had been removed and it formed about 400 µl of viscous liquid. One drop (≈50 µl) was used for Fourier Transform Infrared (FTIR) spectroscopy analysis. The FTIR provides an absorbance spectrum identifying the major chemical bonds representing various classes of biochemical compounds in the bio-oil. The presence and relative abundance of these compounds partly determines the bio-oil's suitability for producing value-added chemicals. The samples were analyzed 1 year apart to determine bio-oil stability after storage. A Varian 800 FTIR spectrophotometer was used for the scans, and each spectrum is the average of 200 scans.

Individual organic compounds are nearly impossible to identify in the FTIR spectrum because bio-oil is a complex mix of 300 or more compounds (Czernik and Bridgwater 2004) with similar overlapping IR spectra shown on the same scan (Figure 5). The spectra suggest that the bio-oil produced using MNR's pyrolysis unit is similar to other biomass-generated bio-oil because it contains mostly oxygenated species, such as phenols, alcohols, ketones, aldehydes, and carboxylic acids (Czernik and Bridgwater 2004).

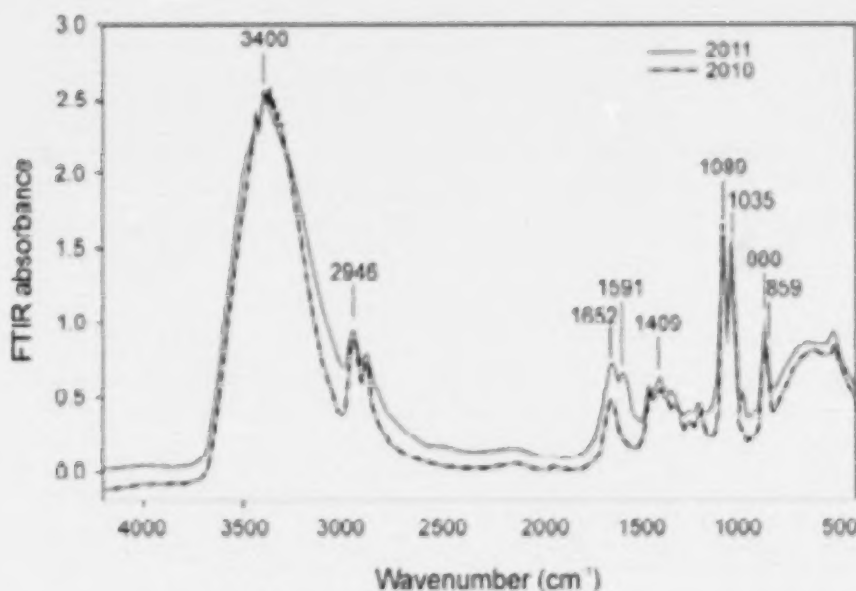


Figure 5. Fourier Transform Infrared absorbance spectrum of bio-oil analyzed after 1 (2010) and 2 (2011) years of storage at 4 °C.

Major peaks include the broad band O-H stretch ($3400\text{--}3375\text{ cm}^{-1}$), indicating hydrogen bonding caused by water, phenols, aldehydes, and alcohols such as vanillin, syringol, and guaiacol, and/or the hydroxyl group of cellulose-derived carbohydrates (Artz et al. 2008) such as levoglucosan and cellobiosan. The shoulder of this peak ($2946\text{--}2948\text{ cm}^{-1}$) is produced from the C-H group of aliphatic alkanes, while the peak at 1409 cm^{-1} is also from the C-H bond of alkanes, indicating hydrocarbons (Coates 2000). Major peaks at 1089 and 1035 cm^{-1} indicate C-O alcohol bonds (Coates 2000), suggesting the presence of alcohols such as syringol and guaiacol, which are derived from lignin (Mathias and Halkar 2004). The peaks in the range of $1500\text{--}1700\text{ cm}^{-1}$ are produced by a C=O carbonyl group, which includes ketones such as hydroxyacetone and aldehydes such as glyoxal, glycoaldehyde, formaldehyde, furfural, and vanillin. In fact, formaldehyde and vanillin could be indicated by the peak at 1652 cm^{-1} (Popova et al. 2007, Li et al. 2008). Although carboxylic acids, such as acetic and formic, are likely found in the bio-oil, the spectra show no strong peaks that indicate their presence so these compounds may have volatilized during the drying of the bio-oil. The peak at 880 cm^{-1} is caused by a C-H out-of-plane bending, which suggests unsaturated organic compounds such as olefins and aromatics (Coates 2000). The last broad peak ($\approx 600\text{--}700\text{ cm}^{-1}$) is also caused by C-H out-of-plane bending, indicating aromatic ring structures such as those in various phenols.

Comparing the 2010 and 2011 spectra reveals that the 2010 bio-oil lacks the 1591 cm^{-1} peak. In the 2011 scan, this peak might have been caused by aging-related reactions of ketones and aldehydes with phenols forming more complex aromatics. Another aging-related chemical reaction that could have caused this shift is the reaction of KOH with carboxylic acids to form carboxylates, which absorb IR in the $1550\text{--}1610\text{ cm}^{-1}$ range (Coates 2000).

In general, the two spectra are quite similar, indicating that the bio-oil is stable when stored in darkness at $4\text{ }^{\circ}\text{C}$ for almost 2 years. This result suggests that bio-oil could be generated in rural areas, transported to biorefineries, and stored under proper conditions for up to 2 years before processing without risking significant chemical changes.

Value-added potential of pyrolysis biochemicals

The diversity of compounds resulting from biomass pyrolysis offers many opportunities. Bio-oil has been tested as a fuel for use in boilers, furnaces, and diesel engines but can also be used as a chemical feedstock to produce value-added biochemicals (Czernik and Bridgwater 2004). Bio-oil is considered a more sustainable alternative to petroleum-based fuels because it is nearly carbon neutral (carbon dioxide released by combustion of bio-oil was fixed by the biomass growth) and renewable (Bridgwater et al. 1999). However, it is only marginally economical as a fuel because, compared with petroleum fuels and natural gas, it has low heating value and is acidic, requiring furnaces and engines to be modified to prevent corrosion (Oasmaa and Czernik 1999). Even compared to pelletized wood, bio-oil fuel is currently not as economical. Thus, increasing production of value-added chemical feedstocks from bio-oil is a key to increasing its profitability. Using a biorefinery is likely the best approach, as bio-oil can be upgraded for both biochemical feedstock use and enhanced fuel properties (Vispute et al. 2010, Vitasari et al. 2011).

Among the many other compounds produced from biomass pyrolysis, liquid smoke™ and condensed natural smoke™ are the only ones that are consistently sold commercially at a profit. Many other compounds can be derived from the carbohydrates and phenolics in bio-oil and used to make biopolymers, adhesives, solvents, lubricants, resins, and drugs. For example, phenolic rich bio-oil generated from softwood bark has successfully replaced up to 35% of the phenol in the phenol-formaldehyde adhesive used for manufacturing oriented strandboard (Chan et al. 2002). These bio-based chemicals have greater value per volume than the pyrolysis-derived fuel (Czernik and Bridgwater 2004). Werpy and Petersen (2004) identified the top 12 potential value-added chemicals that can be produced from biomass, with most found in or derived from bio-oil (Table 2). In an updated review, Bozell and Petersen (2010) removed fumaric, malic, aspartic, glucaric, glutamic, and itaconic acid, citing a lack of recent research activity, but added ethanol, lactic acid, and isoprene (Table 2).

The value-added classes of chemicals most likely to be produced from bio-oil are furans and organic acids derived from sugars, sugar alcohols, and isoprene derived from lignin. For example, Rivertop Renewables built a pilot plant in Montana to produce glucaric acid, which is derived from glucose. Glucaric acid can be used for manufacturing products ranging from solvents and detergent enhancers to polyglucaric esters and amides, which are incorporated into fabrics such as nylon, Kevlar™, and carpet (Werpy and Petersen 2004, Bozell and Petersen 2010, de Guzman 2011). Another potentially profitable biohydrocarbon, isoprene, is found in bio-oil produced from terpenes (Britt et al. 2004) and can be produced from bio-oil using catalysts (Vispute et al. 2010). Isoprene is commonly used to produce synthetic rubber, pesticides, pharmaceuticals, synthetic oil additives, and aviation fuel (Zhao et al. 2010).

To commercially produce these value-added biochemicals from bio-oil, the industry will need improved methods for extracting and purifying target compounds and, synthesizing value-added chemicals from bio-oil chemicals, as well as optimizing the pyrolysis process to maximize production of target compounds.

Table 2. Chemicals from biomass rated as having the most commercial potential as value-added products.

Original list (Werpy and Petersen 2004)	Revised list (Bozell and Petersen 2010)
1,4-diols (succinic, fumaric, malic)	ethanol*
2,5-furan dicarboxylic acid	furans
3-hydroxy propionic acid	glycerol
aspartic acid	biohydrocarbons (isoprene)*
glucaric acid	lactic acid*
glutamic acid	succinic acid
itaconic acid	hydroxypropionic acid
levulinic acid	levulinic acid
3-hydroxybutyrolactone	sorbitol
glycerol	xylitol
sorbitol	
xylitol/arabinitol	

*additions

Challenges to commercialization of bio-oil

Producing value-added chemicals from bio-oil is limited by the lack of efficient, cost-effective processes and technologies (Bozell and Peterson 2010). Because bio-oil is a mixture of hundreds of compounds, isolating and purifying just one is complex and expensive (Czernik and Bridgwater 2004). Finding better methods to produce these high value chemicals will economically support production of less profitable biofuels in the highly competitive fuel market (Chheda et al. 2007). The lack of understanding of the chemical reaction mechanisms that form these chemicals during pyrolysis is a significant impediment to developing better production methods for improved biofuels and valuable chemicals from bio-oil (Mettler et al. 2012).

Researchers have made progress in modifying bio-oil to yield more value-added chemicals. For example, Naik et al. (2010) and Vispute et al. (2010) have proposed a detailed integrated biorefinery concept and related technological improvements. And more efficient and higher yield biorefinery production methods are being developed for valuable organic platform chemicals such as benzene, xylene, toluene, and olefins that rely on catalysts and hydrogenation (Adjaye and Bakhshi 1995, Vispute et al. 2010). The integrated biorefinery involves combining cutting-edge thermochemical (pyrolysis), biochemical, and microbiological conversion technologies into one facility that uses the most efficient technology to produce biofuels and/or biochemicals (Naik et al. 2010). As methods advance, this approach will allow manufacturers to use the best conversion technology without building new infrastructure.

Ideally, bio-oil would become a *drop-in* fuel, one that can be used without modifying existing infrastructure. During the last 5 years, U.S. research priorities have moved away from cellulosic ethanol production to biomass conversion to more environmentally sound gasoline (Regalbuto 2011), as prescribed in the Roadmap for Bioenergy and Biobased Products in the United States (Anonymous 2007). Recent results show that *grassoline* can be produced for less than US\$3 a gallon, as long as inexpensive feedstock is available (Savage 2011). Annellotech is scheduled to complete a pilot plant that can produce 2 tons per day by 2014 (Lane 2010). Another company, Dynamotive, has estimated that it can upgrade its bio-oil to green gasoline for as little as \$2 CAN a gallon (Anonymous 2009). However, a more recent, realistic, and detailed techno-economic estimate of the cost of an efficient chemical method to convert biomass (in this case loblolly pine wood) to green gasoline was US\$4.31 a gallon (Sen et al. 2012). Although converting biomass is more expensive than the current Canadian and U.S. price for petroleum-based gasoline, it should become more economical as the technology improves and crude oil prices inevitably rise.

Another major challenge for the bio-oil value-added industry is finding dependable sources of inexpensive biomass (Anonymous 2007). Although sustainably harvested biomass could supply up to one third of the future global energy demand (Dornburg et al. 2010), the feedstock is usually dispersed throughout rural areas, making harvest and transportation to biorefineries expensive (Richard 2010). Developing cost-efficient forest biomass harvesting equipment designed for bioenergy and bioproducts is just beginning. MNR's portable pyrolysis unit is an example of equipment that reduces transport costs since it can be moved to field sites to transform bulky forest biomass into 6 to 7 times more energy-dense bio-oil, which is cheaper to ship. Another issue is producing enough—and pure enough—feedstock to meet biorefinery supply specifications (Anonymous 2007).

Pioneering pyrolysis companies, such as Dynamotive, Ensyn, and Woodland Biofuels have begun to address these challenges by creating a global network of partners attempting to develop profitable technologies for sustainable fuel and chemical production, with several initiatives slated for 2012. For example, Dynamotive, based in Vancouver, Canada, recently joined a consortium including Renewable Oil Corporation, Virgin Australia, and General Electric-Australia to build a pilot plant to convert eucalyptus biomass into bio-oil and upgrade it into commercial jet fuel (Dynamotive 2011b). Based in Wilmington, Delaware, Ensyn, a leader in developing 30 food products from bio-oil with Red Arrow, is now working with Italy's Industria e Innovazione to build a 150 ton day⁻¹ pyrolysis unit to convert forest residues from local sources into bio-oil for upgrading into biodiesel to generate electricity (Ensyn 2011a). Ensyn is also working with Premium Renewable Energy of Malaysia to build a 400 ton day⁻¹ pyrolysis plant in Borneo that will convert oil palm biomass residues into renewable fuel oil to produce electricity (Ensyn 2011b). Finally, Woodland Biofuels, based in Mississauga, ON, recently completed, at Western University Research Park's Bioindustrial Innovation Centre in Sarnia, ON, their demonstration plant for pyrolyzing woody and agricultural biomass into syngas, which

is then catalytically converted to ethanol. Ongoing collaboration among leading pyrolysis companies and innovative industrial partnerships demonstrates that pyrolysis technology is on the cusp of commercial viability.

Using pyrolysis to convert woody biomass to bio-oil and bioproducts as a replacement for petroleum products has many potential environmental and economic benefits (Mohan et al. 2006). Environmental benefits include producing fuel and chemicals from a renewable resource, lowering net carbon dioxide emissions, and reducing dependence on a diminishing supply of oil. Economic benefits include developing rural economies to provide a sustainable, secure feedstock source for fuel and industrial chemical production and possibly generating industrial carbon credits (Naik et al. 2010, Sheldon 2011). However, to expand markets for fuel and chemicals created from bio-oil in the future, more research and technology development is needed, especially in methods for greater production and efficient purification of valuable chemicals from bio-oil and upgrading bio-oil into *drop-in* fuels. To help spur such research, MNR has transferred ownership of its prototype portable pyrolysis unit to Laurentian University.

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References

- Adjaye, J.D. and N.N. Bakhshi. 1995. Production of hydrocarbons by catalytic upgrading of a fast pyrolysis bio-oil. Part I: Conversion over various catalysts. *Fuel Proc. Tech.* 45: 161-183.
- Anonymous 2007. Roadmap for bioenergy and biobased products in the United States. In Biomass Research and Development Technical Advisory Committee, Biomass Research and Development Initiative. 46 p. Available at http://www.usbiomassboard.gov/pdfs/obp_roadmapv2_webkw.pdf; accessed October 2012.
- Anonymous 2009. Dynamotive produces renewable gasoline and diesel from biomass in three-stage process: pyrolysis, hydroreforming, hydrotreating. Available at <http://www.greencarcongress.com/2009/04/dynamotive-bingo-20090425.html>; accessed October 2012.
- Artz, R.R.E., S.J. Chapman, A.H. Jean Robertson, J.M. Potts, F. Laggoun-Défarge, S. Gogo, L. Comont, J.-R. Disnar and A.-J. Francez. 2008. FTIR spectroscopy can be used as a screening tool for organic matter quality in regenerating cutover peatlands. *Soil Biol. Biochem.* 40: 515-527.
- Badger, P.C. and P. Fransham. 2006. Use of mobile fast pyrolysis plants to densify biomass and reduce biomass handling costs—A preliminary assessment. *Biomass Bioenergy* 30: 321-325.
- Bomgardner, M. 2011. Making rubber from renewables. *Chem. Eng. News* 89: 18-19.
- Bozell, J.J. and G.R. Petersen. 2010. Technology development for the production of biobased products from biorefinery carbohydrates—the US Department of Energy's "Top 10" revisited. *Green Chem.* 12: 525-728.
- Bridgwater, A.V., P. Carson and M. Coulson. 2007. A comparison of fast and slow pyrolysis liquids from mallee. *Int. J. Global Energy Issues* 27: 204-216.
- Bridgwater, A.V., D. Meier and D. Radlein. 1999. An overview of fast pyrolysis. *Org. Geochem.* 30: 1479-1493.
- Britt, P.F., A.C. Buchanan and C.V. Owens Jr. 2004. Mechanistic investigation into the formation of polycyclic aromatic hydrocarbons from the pyrolysis of terpenes. *Prepr. Pap.-Am. Chem. Soc., Div. Fuel Chem.* 49: 868-871.
- Carlson, R. 2011. Biodesic 2011 bioeconomy update. Available at http://www.biodesic.com/library/Biodesic_2011_Bioeconomy_Update.pdf; accessed October 2012.
- Chan, F., B. Riedl, X. M. Wang, X. Lu, C. Amen-chen, and C. Roy. 2002. Performance of pyrolysis oil-based wood adhesives in OSB. *For. Prod. J.* 52(4): 31-38.
- Chhedha, J.N., G.W. Huber, and J.A. Dumesic. 2007. Liquid-phase catalytic processing of bio-mass derived oxygenated hydrocarbons to fuels and chemicals. *Angewandte Chemie* 46: 7164-7183.
- Coates, J. 2000. Interpretation of infrared spectra, a practical approach. Pp. 10815-10837 in R. A. Meyers (ed.). *Encyclopedia of Analytical Chemistry*. John Wiley & Sons Ltd., Chichester, UK.
- Czemik, S. and A.V. Bridgwater. 2004. Overview of applications of biomass fast pyrolysis oil. *Energy Fuels* 18: 590-598.

- de Guzman, D. 2011. Rivertop to start pilot plant construction. ISCS Green Chemicals. Available at <http://www.icis.com/blogs/green-chemicals/2011/04/rivertop-to-start-pilot-plant.html>; accessed October 2012.
- Diebold, J.P. 2000. A review of the chemical and physical mechanisms of the storage stability of fast pyrolysis bio-oils. National Renewable Energy Laboratory, Golden, CO. Report No. NREL/SR-570-27613. Available at http://webdev.its.iastate.edu/webnews/data/site_biorenew_reading/19/webnewsfilefield_file/ReviewOfMechanisms.pdf; accessed October 2012.
- Dornburg, V., D. van Vuuren, G. van de Ven, H. Langeveld, M. Meusen, M. Banse, M. van Oorschot, J. Ros, G.J. van den Born, H. Aiking, M. Londo, H. Mozaffarian, P. Verweij, E. Lyseng, and A. Faaij. 2010. Bioenergy revisited: Key factors in global potentials of bioenergy. *Energy Environ. Sci.* 3: 258-267.
- Dynamotive. 2011a. BioOil information booklet. Available at <http://www.sustainablenorthwest.org/resources/biomass/DynaMotive%20BioOil%20Book.pdf>; accessed October 2012.
- Dynamotive. 2011b. Dynamotive announces that GE joined consortium established to develop Australian biofuel. Available at <http://www.dynamotive.com/2011/09/01/dynamotive-announces-that-ge-joined-consortium-established-to-develop-australian-biofuel/>; accessed October 2012.
- Ensyn Technologies. 2011a. Green electricity for Italy. Available at <http://www.ensyn.com/projects/indi-projectitaly/>; accessed October 2012.
- Ensyn Technologies. 2011b. Ensyn and Premium team up to produce renewable fuels in Malaysia and Indonesia. Available at <http://www.ensyn.com/partners/premium-renewable-energy/>; accessed October 2012.
- Farag, I.H., C.E. LaClair and C.J. Barrett. 2002. Final report: Technical, environmental and economic feasibility of bio-oil in New Hampshire's north country. Available at <http://www.unh.edu/p2/biooil/bounhif.pdf>; accessed October 2012.
- [FPAC] Forest Products Association of Canada. 2010. Transforming Canada's forest products industry: Summary of findings from the future bio-pathways project. Available at <http://www.fpac.ca/publications/Biopathways%20ENG.pdf>; accessed December 2012.
- Hayden, E. C. 2011. Renewable rubber hits the road. Available at <http://www.nature.com/news/2011/110930/full/news.2011.568.html>; accessed October 2012.
- Hosoya, T., H. Kawamoto and S. Saka. 2007. Pyrolysis behaviours of wood and its constituent polymers at gasification temperature. *J. Anal. Appl. Pyrolysis* 78: 328-336.
- [IEA] International Energy Agency. 2007. Annual report 2006 IEA Bioenergy. Available at <http://www.ieabioenergy.com/DocSet.aspx?id=5566&rel=lib> [Accessed October 2012].
- Laird, D.A., R.C. Brown, J.E. Amonette and J. Lehmann. 2009. Review of the pyrolysis platform for coproducing bio-oil and biochar. *Biofuels Bioprod. Bioref.* 3: 547-562.
- Lane, J. 2010. New breakthrough in pyrolysis sector promises to speed commercialization. Available at <http://biofuelsdigest.com/bdigest/2010/11/26/new-breakthrough-in-pyrolysis-sector-promises-to-speed-commercialization/>; accessed October 2012.
- Li, X., S. Deng, H. Fu, G. Muc and N. Zhao. 2008. Synergism between rare earth cerium(IV) ion and vanillin on the corrosion of steel in H₂SO₄ solution: Weight loss, electrochemical, UV-vis, FTIR, XPS, and AFM approaches. *Appl. Surf. Sci.* 254: 5574-5586.
- Mathias, E.V. and U.P. Halkar. 2004. Separation and characterization of lignin compounds from the walnut (*Juglans regia*) shell oil using preparative TLC, GC-MS and ¹H NMR. *J. Anal. Appl. Pyrolysis* 71: 515-524.
- Mettler, M. S., D. G. Vlachos, and P. J. Dauenhauer. 2012. Top ten fundamental challenges of biomass pyrolysis for biofuels. *Energy Environ. Sci.* 5: 7797-7809.
- Mohan, D., C.U. Pittman and P.H. Steele. 2006. Pyrolysis of wood/biomass for bio-oil: A critical review. *Energy and Fuels* 20: 848-889.
- Naik, S.N., V. V. Goud, P.K. Rout and A.K. Dalai. 2010. Production of first and second generation biofuels: A comprehensive review. *Renew. Sust. Energy Rev.* 14: 578-597.
- Oasmaa, A. and S. Czernik. 1999. Fuel oil quality of biomass pyrolysis oils—state of the art for the end users. *Energy Fuels* 13: 914-921.
- Popova, G.Y., T.V. Andrushkevich, Y.A. Chesalov and V.N. Parmon. 2007. Transient response study of the formaldehyde oxidation to formic acid on V-Ti-O catalyst: FTIR and pulse study. *J. Mol. Cat. A: Chemical* 268: 251-258.
- Regalbuto, J.R. 2011. The sea change in US biofuels' funding: from cellulosic ethanol to green gasoline. *Biofuels, Bioprod. Bioref.* 5: 495-504.
- Richard, T.L. 2010. Challenges in scaling up biofuels infrastructure. *Science* 329: 793-796.
- Savage, N. 2011. Fuel options: the ideal biofuel. *Nature* 474: 9-11.
- Sen, S.M., C.A. Henao, D.J. Braden, J.A. Dumesic and C.T. Maravelias. 2012. Catalytic conversion of lignocellulosic biomass to fuels: process development and techno-economic evaluation. *Chem. Eng. Sci.* 67: 57-67.
- Sheldon, R.A. 2011. Utilisation of biomass for sustainable fuels and chemicals: Molecules, methods and metrics. *Catalysis* 167: 3-13.
- Tsai, W.T., M.K. Leeb and Y.M. Chang. 2007. Fast pyrolysis of rice husk: Product yields and compositions. *Bioresour. Tech.* 98: 22-28.

- van Haveren, J., E.L. Scott and J. Sanders. 2007. Bulk chemicals from biomass. *Biofuels Bioprod. Bioref.* 2: 41-57.
- Vispute, T. P., H. Zhang, A. Sanna, R. Xiao and G.W. Huber. 2010. Renewable chemical commodity feedstocks from integrated catalytic processing of pyrolysis oils. *Science* 330: 1222-1227.
- Vitasari, C.R., G.W. Meindersma and A.B. de Haan. 2011. Water extraction of pyrolysis oil: The first step for the recovery of renewable chemicals. *Bioresour. Tech.* 102: 7204-7210.
- Werpy, T. and G. Petersen. 2004. Top value added chemicals from biomass: Volume I—Results of screening for potential candidates from sugars and synthesis gas. US Dept. Energy, Pac. Northw Nat. Lab/Nat. Renewable Energy Lab, Rep. No. DOE/GO-102004-1992, 76 p.
- Zhang, Q., J. Chang, T. Wang and Y. Xu. 2007. Review of biomass pyrolysis oil properties and upgrading research. *Energy Conver. Manage.* 48: 87-92.
- Zhao, Y., L. Deng, B. Liao, Y. Fu and Q.-X. Guo. 2010. Aromatics production via catalytic pyrolysis of pyrolytic lignins from bio-oil. *Energy Fuels* 24: 5735-5740.

Résumé

Un prototype d'une unité mobile de pyrolyse de la biomasse et son potentiel pour produire des produits chimiques et des combustibles et à valeur ajoutée

Les réserves de pétrole du monde ne dureront pas infiniment et leur utilisation dans la production de combustibles augmente les émissions de gaz à effet de serre qui contribuent au changement climatique. La biomasse renouvelable constitue une solution prometteuse aux produits à base de pétrole comme source de bioénergie et d'autres bioproduits (p. ex., produits chimiques à valeur ajoutée, additifs alimentaires), mais elle représente seulement une portion mineure du marché mondial. Nous décrivons un prototype d'une unité mobile de pyrolyse rapide fabriqué en Ontario à titre d'exemple d'une technologie émergente de conversion de la biomasse. Nous résumons également les utilisations possibles de la bio-huile pour des produits chimiques et des biocombustibles à valeur ajoutée. Les défis posés par la commercialisation de cette technologie émergente sont également abordés.